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The SATRAK Simulator

30 MARCH 1963

Prepared by
C. H. BREDALL

Prepared for COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

ENGINEERING DIVISION • AEROSPACE CORPORATION
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ABSTRACT

The SATRAK Simulator (SAtellite TRajectory and Attitude Kinematic Simulator) is an instrument which can quickly measure simulated satellite aspect as a function of sensor location, satellite trajectory, satellite attitude, and time. The instrument can simulate circular orbits of altitudes from 80 to 440 nautical mile range and for any inclination angle. Design accuracy for deriving aspect angles is within two degrees.

This report defines the SATRAK; describes components of the instrument; provides typical examples of its function; defines the accuracy as well as the limitations of the instrument; and discusses the type of problems which it can solve.

The instrument's parts are described in detail sufficient to permit model construction.

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THE SATRAK SIMULATOR

(SAtellite TRajectory and Attitude Kinematic Simulator)

1.0 INTRODUCTION

The SATRAK Simulator is an instrument useful in setting up and solving problems involving satellite aspect as a function of sensor location, satellite trajectory, satellite attitude, and time. Although the SATRAK was designed primarily for an earth-based sensor such as a ground tracking radar, it may also be used to solve problems generated by co-orbiting satellites and provides direct, mutual aspect solutions. SATRAK means SAtellite TRajectory and Attitude Kinematic Simulator.

2.0 GENERAL DESCRIPTION

The instrument consists of

- a. a base plane, located for mechanical convenience 300 scaled nautical miles below the observation point
- b. azimuth and elevation protractors located at the observation point
- c. movable trajectory cards which provide the track upon which the satellite model rides
- d. the satellite model bearing an attitude indicator which automatically points along the line of sight from the observation point to the satellite for all satellite positions.

The base is marked off in equally spaced concentric circles which serve as earth range references for setting up the trajectory cards. The upper edge of the trajectory card, which forms a track for the model, is marked off in equal increments of in-track range. With constant velocity these become equal increments of time. The satellite is treated as a point in space in setting up the problems. However, for reading aspects, a hemispherical graticule is provided, its surface engraved at each 10 degrees in the conventional

Theta (θ) and Phi (ϕ) angles (see Figure 1). The graticule is transparent to permit viewing an enclosed representative satellite model with its center of gravity located at the referenced satellite point and its principal axis aligned with the axis of the graticule sphere.

Yaw, pitch, and roll can be set into the satellite model. A set screw is loosened to permit rotation about the vertical shaft for yaw adjustment. Angle indications are provided. Pitch is achieved by moving the thumb screw and rotating the hemisphere about its transverse axis. Again, an angle scale is provided. Roll is provided by means of an indicator, or fiducial, located inside the transparent graticule which establishes the roll reference as either 0 to 180 degrees or 180 to 360 degrees, depending on the direction of the satellite nose. Altitude is adjustable by introducing various length sections between the satellite support base and the satellite. The SATRAK has been built to a scale of 50 nautical miles to the inch. The altitude sections for this scale are 10, 20, 40, and 80 nautical miles. These can be assembled in any combination; for example, altitude can be simulated in 10 nautical mile steps from a minimum altitude of 80 nautical miles to a maximum of 220 nautical miles. If the scale is doubled, this range would be 160 to 440 nautical miles in 20 nautical mile steps. Zero elevation limits are encountered above 180 nautical miles for the basic scale, and above 360 nautical miles for the doubled scale. A more detailed description is given in Section 4, Construction. Several views of the SATRAK are furnished in Figures 2, 3, 4, and 5.

3.0 USE

3.1 TYPES OF PROBLEMS

It is not intended to enumerate all possible uses of the SATRAK, but rather to give typical examples of its use.

3.1.1 Universal Aspect Traces

When the SATRAK is set up, as shown in Figure 6, the individual tracks are located at equal intervals from the observation point and perpendicular to the vertical plane formed by the satellite and observation point at

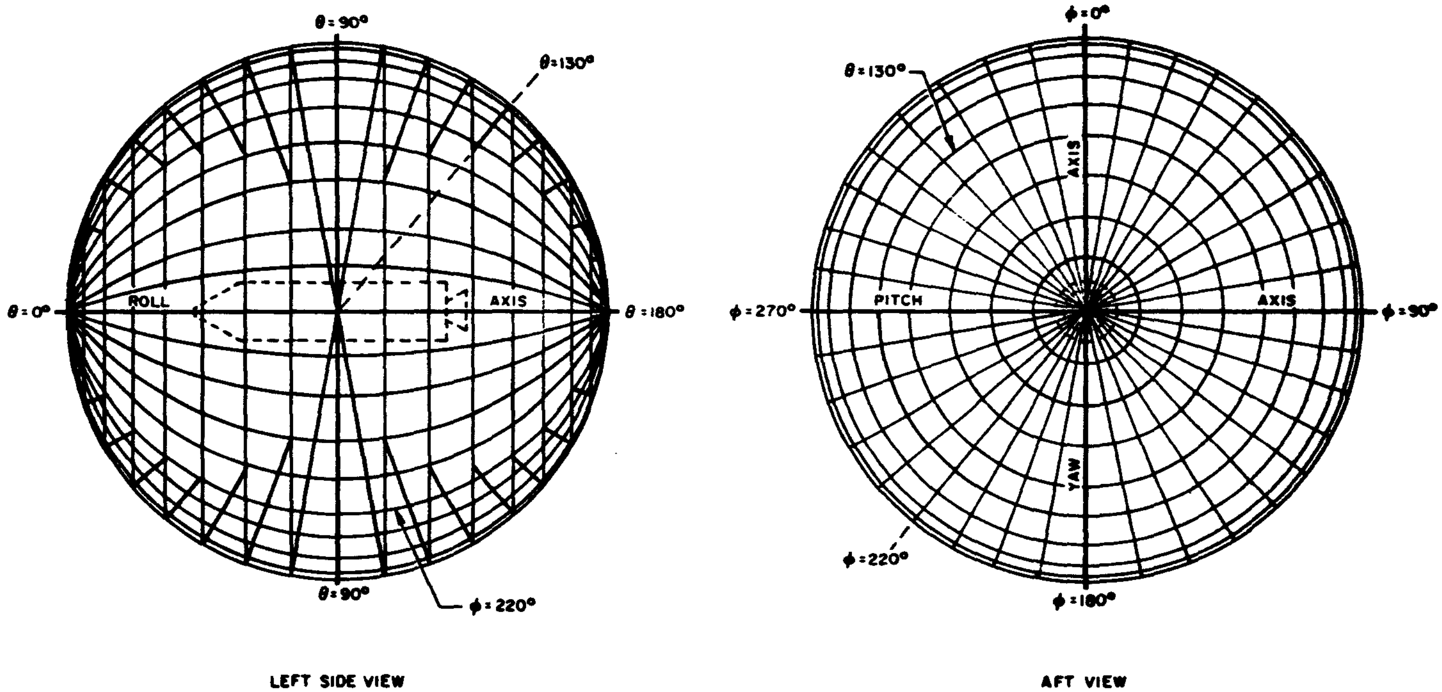


Figure 1. θ, φ Aspect Conventions

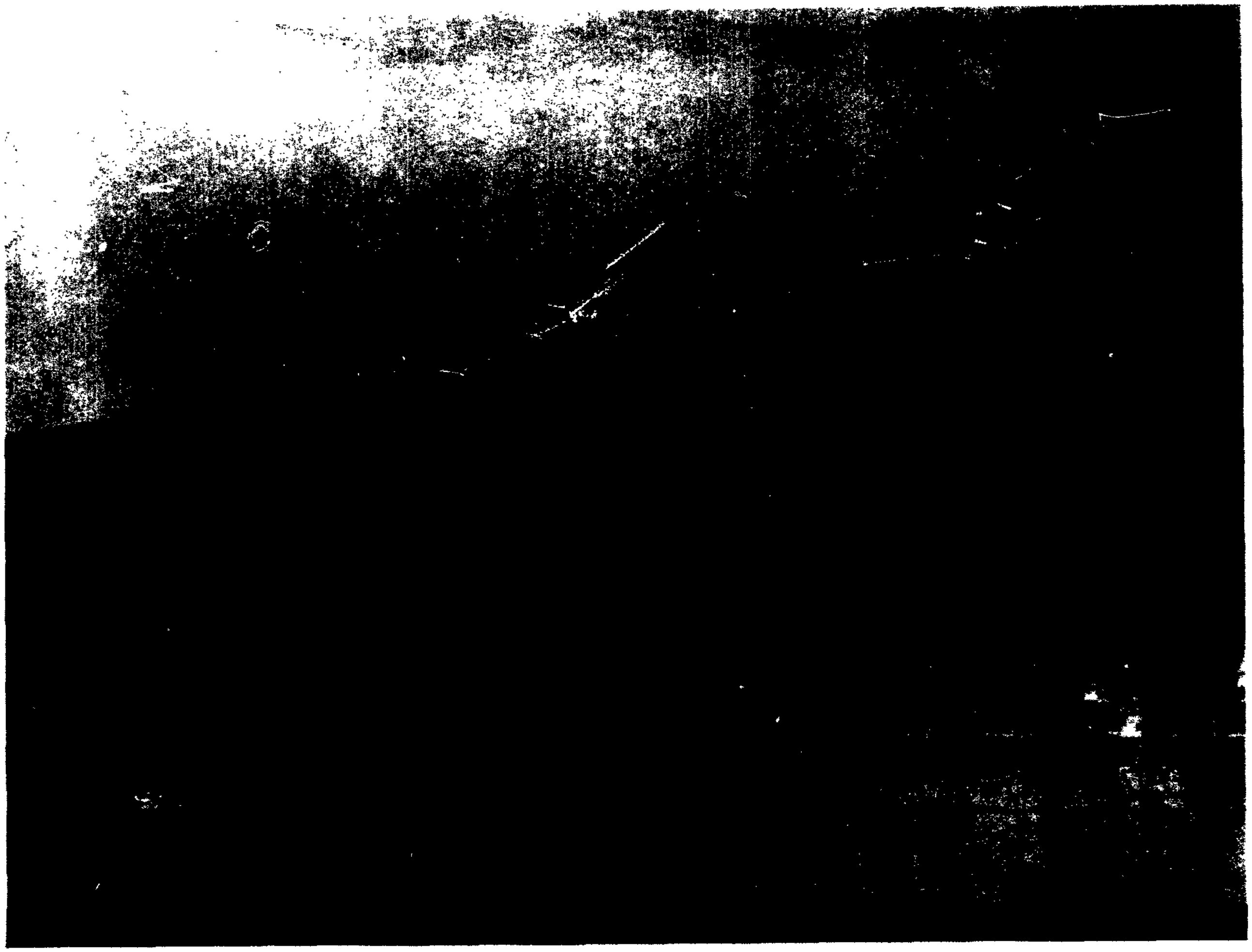


Figure 2. SATRAK Simulator (Front View) Vehicle in Stabilized Position at 120 nautical miles Simulated Altitude

Figure 3. SATRAK Simulator (View Showing Trajectory Card Angles and Range Marks)

Figure 4. SATRAK Simulator (View Showing Azimuth and Elevation Indicators of Simulated Radar)

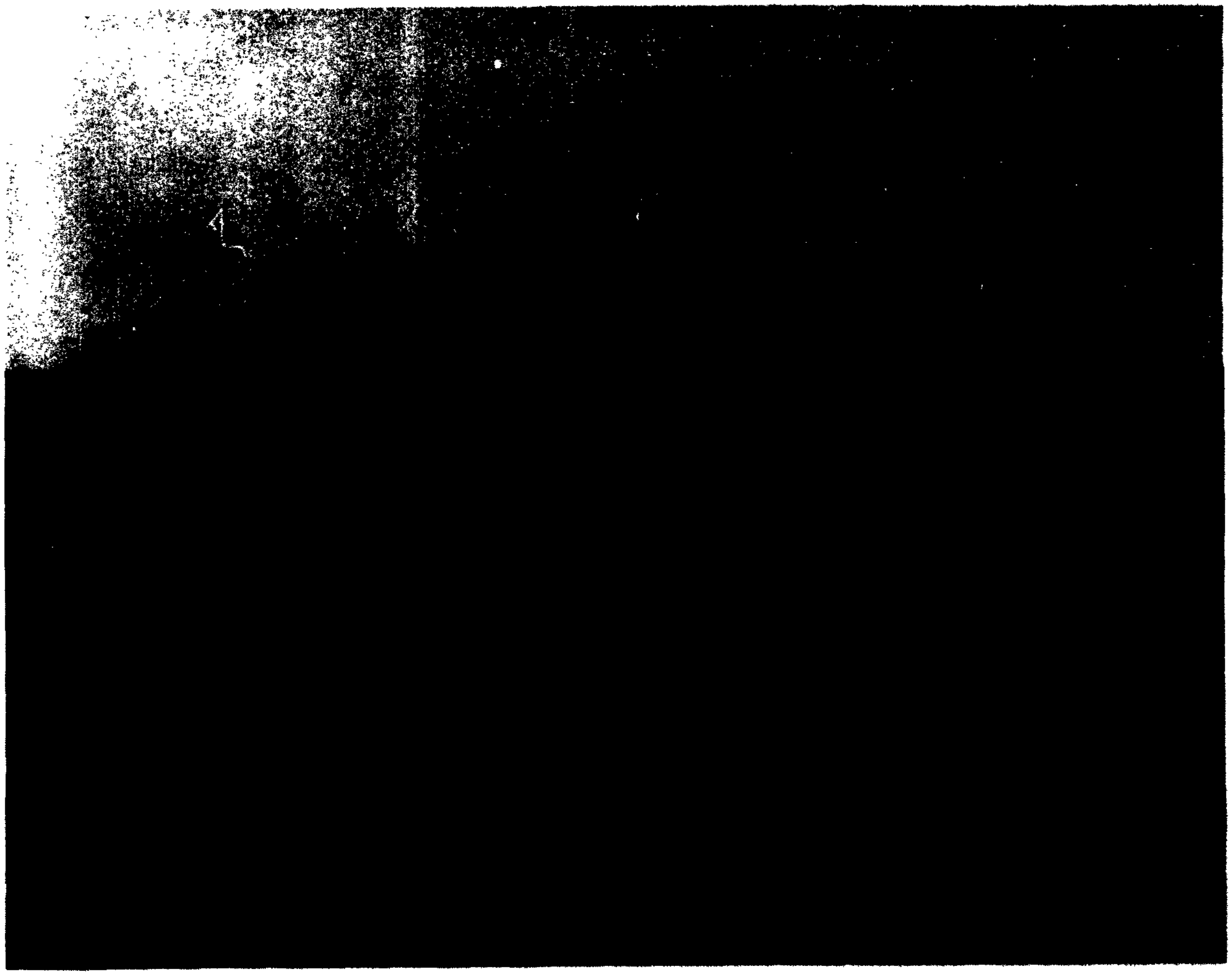


Figure 5. SATRAK Simulator Rear View

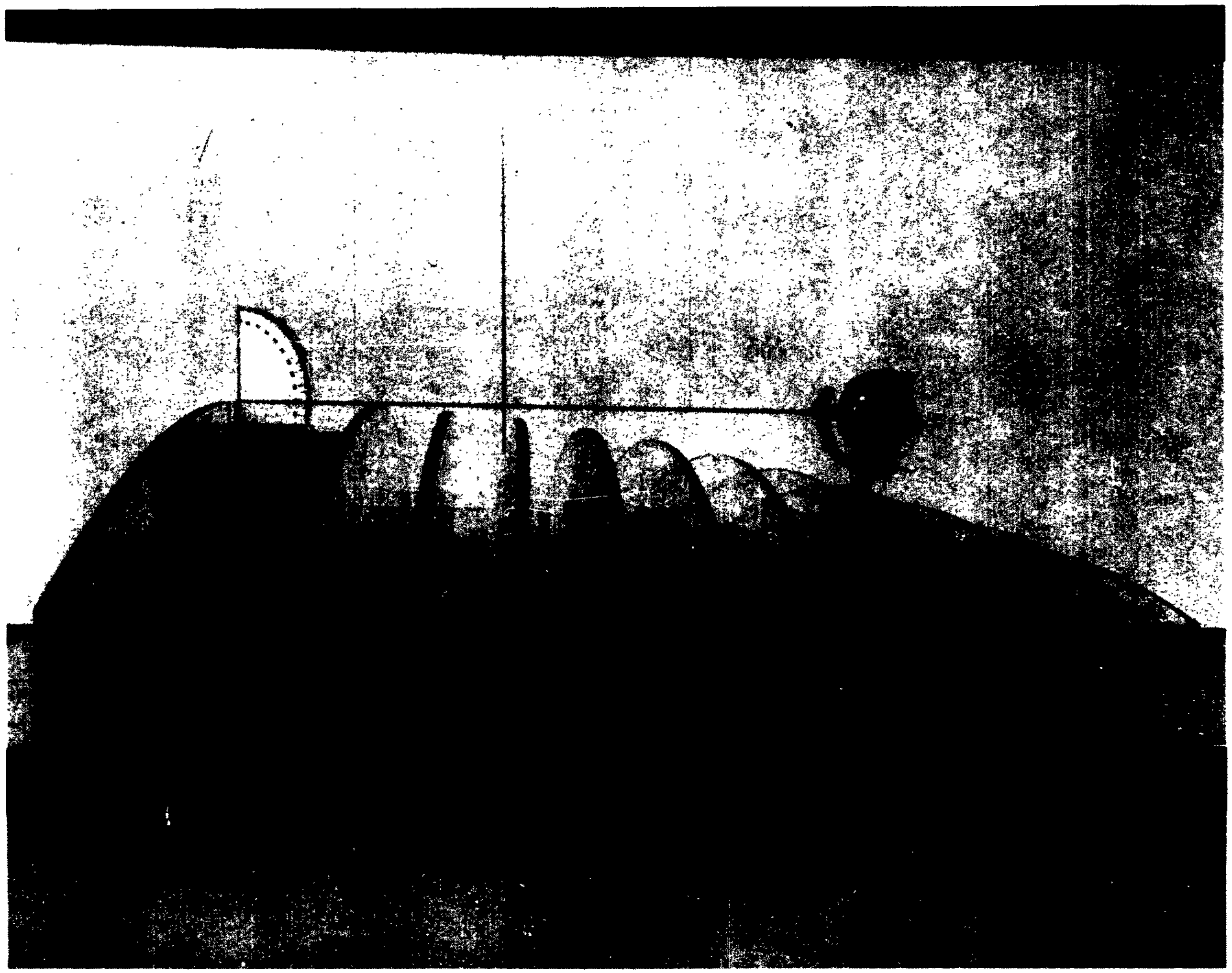


Figure 6. SATRAK Simulator Side View

midpass. Thus set up, the satellite model is placed on one of the tracks and moved until the elevation indication is zero. This is the condition of rise or fade, depending on the simulated direction of flight. Assuming rise, the indication of the pointer opposite the graticule is read observing the established reference in terms of θ and ϕ. Subsequent positions along the track permit, in succession, readings of θ and ϕ which result in a data set of aspect throughout a simulated pass from rise to set. This results in a family of aspect traces which can be plotted on rectilinear paper as a function of θ and ϕ. (See Figure 7.) Time ticks are determined by dividing the incremental distances moved along the track by the satellite's in-track velocity and can be placed on the aspect traces. The family of curves will be universal for any inclination angle but unique for the particular altitude simulated. A similar family of aspect traces will obtain for each altitude simulated. From these data statistical distribution of aspects can be derived.

3.1.2 Specific Trajectory

In order to set up a problem simulating a specific trajectory relative to a designated earth-based sensor, it is necessary to resort to some other device. Three such devices are: (1) computer-determined orbital ephemeris, (2) manually-determined orbital ephemeris, or (3) ground trace determination by use of a Ground Trace Calculator. When the orbital ephemeris is to be used for a particular pass, the SATRAK is set up by applying the indicated azimuth, elevation, and range to obtain positioning of the trajectory card. A good starting point is the azimuth of the highest elevation occurring during the pass. For this condition, the satellite model adjusted to the proper altitude is placed on the center line of the particular card and azimuth is read at the simulated radar (observation point). At this position, the plane of the card is tangent to the base circle representing surface range to the ground trace. Slant range from the radar to the satellite can be read along the line of sight. In this position elevation can be read and checked against the ephemeris.

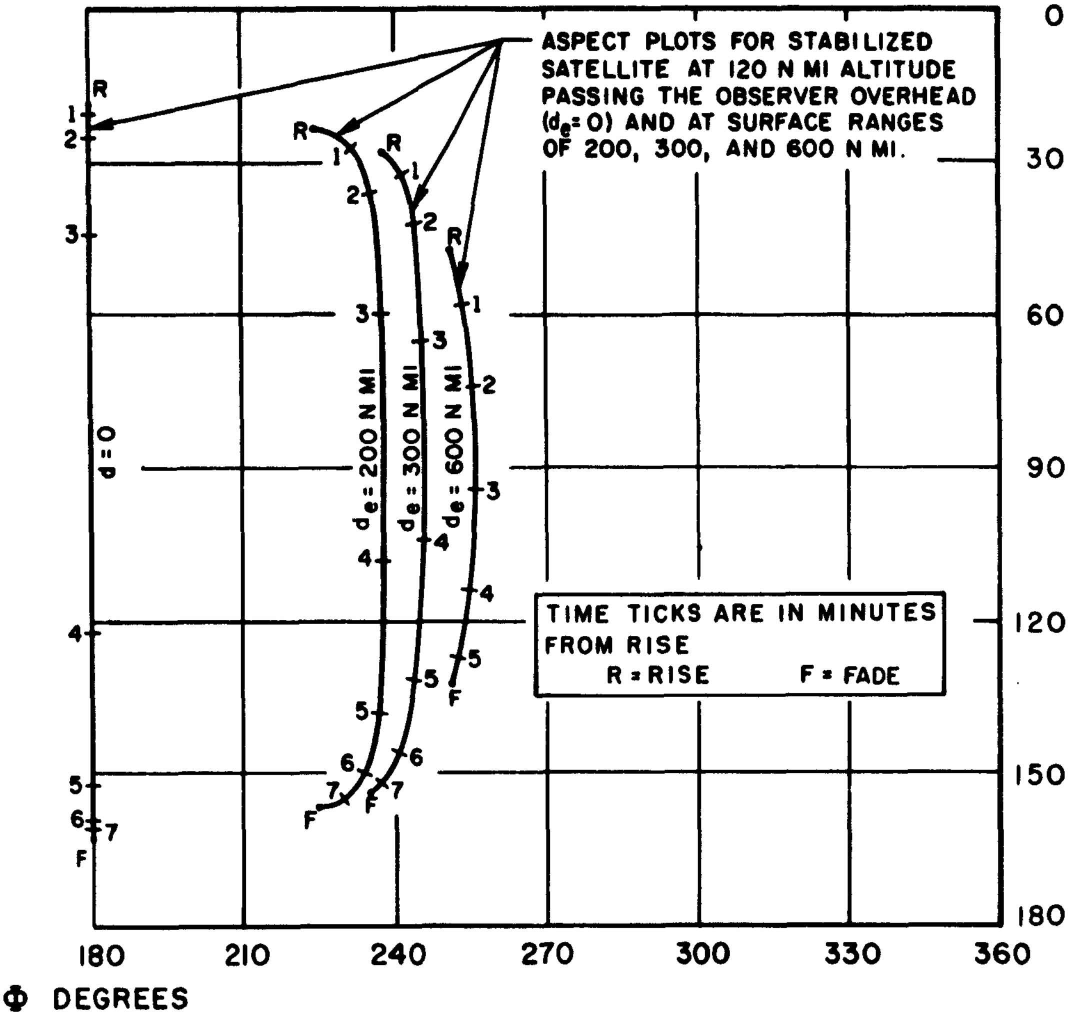


Figure 7. Family of Aspect Traces Derived from SATRAK

In the Ground Trace Calculator shown in Figure 8, representative orbital traces have been applied on a rotating transparent overlay of the projected Northern hemisphere. (It is necessary to prepare range circles and bearing lines for tracking stations of interest, four of which may be seen in Figure 8.) Taking as an example the Vandenberg Tracking Station and a 120 degree inclination angle, it may be seen that the ground trace passes at the closest point 600 nautical miles from the station at an azimuth of 238 degrees. Furthermore, intersections of the ground trace occur on the 800 nautical mile circle at 197 degrees and 281 degrees azimuth. Although there is some curvature to the ground trace, it is not present in the flight trajectory. Setting up the problem in this way takes into account earth's rotation in establishing the trajectory. Earth rotation occurring while the satellite traverses the region of observation introduces error too small to consider for these low altitudes. It is apparent that the range circles provided on the Ground Trace Calculator and the range circles provided on the base of the SATRAK are directly related. It can also be seen that if the base reference line passing through the observer position represents north or south, bearing indications on the Ground Trace Calculator are directly related to azimuth angles as read on the SATRAK radar simulator. When the SATRAK has been set up in this fashion, the pass may be simulated by moving the satellite model along the track from rise to set and by observing azimuth, elevation, and slant range from the radar simulator and the θ and ϕ angles from the satellite model. The range circles and bearing lines provided on the Ground Trace Calculator are useful for all altitudes up to that which establishes the maximum range of visibility. When higher altitudes are desired, the circles must be extended accordingly.*

Once the aspect determinations have been made with desired yaw, pitch, and roll having been set into the satellite model, these traces can be related directly to antenna patterns, satellite-based sensor patterns and back-scattering patterns. When such patterns are presented on a θ/ϕ plot in the form of contours, the aspect traces plotted with the same scale on transparent

*Range circle reticles shown in Figure 8 accommodate altitudes up to 125 nautical miles.

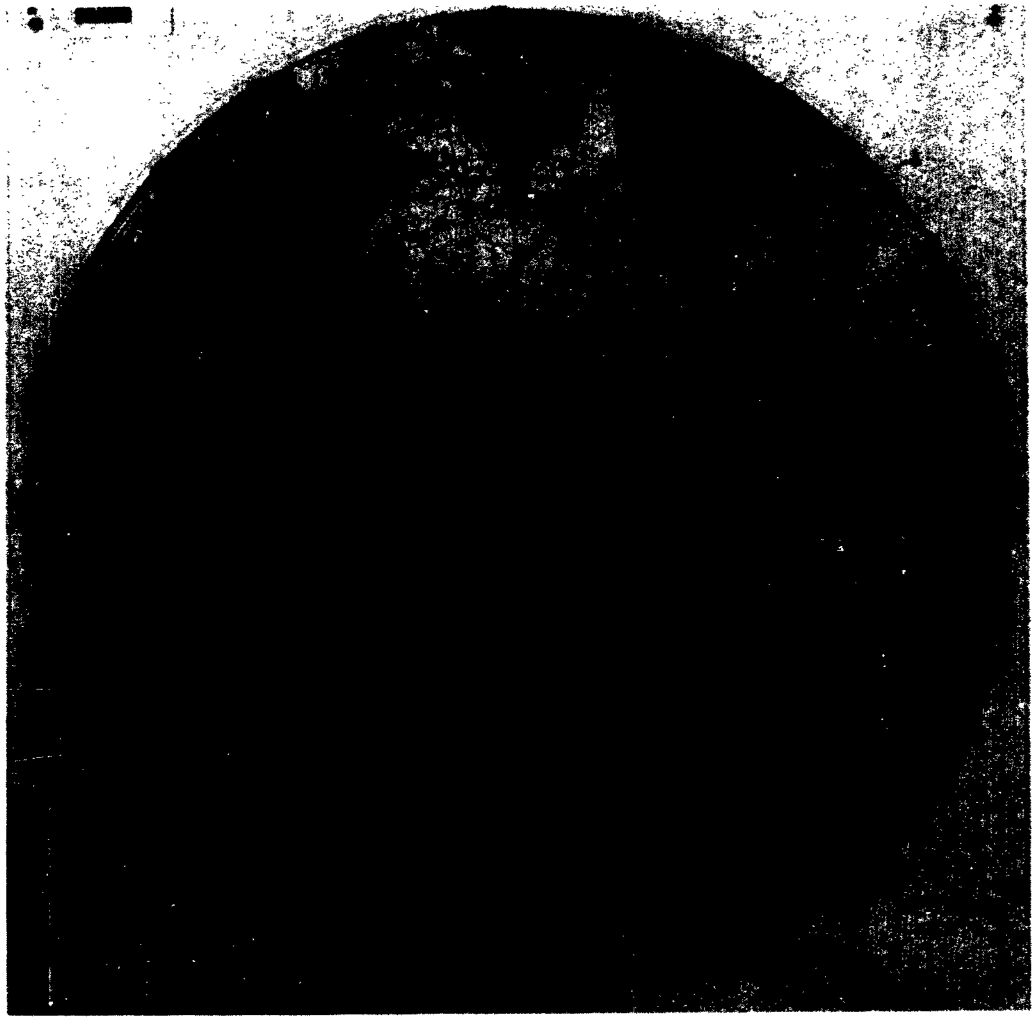


Figure 8. Ground Trace Calculator

paper can be used as overlays to relate aspects with satellite properties and configuration.

3.2 LIMITATIONS

The SATRAK was designed primarily for circular orbits in the 80 to 440 nautical mile altitude range and for any inclination angle. Special treatment must be given to highly elliptical orbits.

3.2.1 Elliptical Orbits

The trajectory cards are cut with a fixed radius equal to the scaled radius of the earth and are thus circular arcs. When the satellite model is moved across on one of these tracks, the trajectory described by the satellite is also a circular arc. In order to simulate the ephemeris of a highly elliptical orbit, it is necessary to re-establish altitude throughout the simulated pass. Inasmuch as altitude is adjustable in increments of ten miles with the present model, some compromise is necessary. Smaller increments could be provided if desired.

3.2.2 Range and Bearing Circles for the Ground Trace Calculator

It is advisable from the standpoint of accuracy to prepare an overlay of range circles and bearing lines for each latitude of interest. Once prepared, the overlay is useful for any longitude provided the proper latitude is observed.

3.3 ACCURACIES

3.3.1 Inherent Accuracy

The inherent or design accuracy of the SATRAK is to within one percent and a few tenths of a degree for azimuth and elevation limitations as read on the simulated radar. In practice, errors in deriving aspect angles have been generally held to 1-2 degrees.

3.3.2 Accuracy of the Satellite Graticule

Accuracy of reading θ and φ depends upon the region of the satellite graticule at which the angle is read, as may be seen on Figure 9. Theta is divided into 10 degree increments equally separated throughout the graticule about three-sixteenths of an inch apart. Figure 9A shows identification of angles. Theta increments are also 10 degrees, but being great circles converge from three-sixteenths of an inch separation at θ equal to 90 degrees, to zero separation at θ equal to zero and 180 degrees. Thus reading inaccuracies are introduced in the regions around θ equal to zero and 180 degrees. Fortunately this is not a region of interest for a stabilized vehicle. If the graticule is not a true hemisphere, or if engraving is not done accurately, additional errors will result.

3.3.3 Trajectory Card Error

The trajectory cards are set at an angle that increases 1.67 degrees for each 100 nautical miles surface range from the observer. This is true because the orbital plane always intersects the earth's center. Therefore, a particular card cut with a height and angle accurate for a particular surface range introduces an error when placed at surface ranges ±50 nautical miles from its design center. These errors are compensatory, however, resulting in a maximum error (θ or φ) of 0.8 degree. Whether θ or φ is most affected depends on the particular simulated satellite attitude. This error can be eliminated by cutting a card for the particular ground range of interest and supporting it at the appropriate angle.

3.3.4 Errors in Setting Up SATRAK

Other errors are introduced in setting up the card position, the extent of error being a function of the technique used. Using a Ground Trace Calculator with a 3 foot diameter circle as indicated in Figure 8, angular error can be held to about one degree. Although the ground trace appears quite curved for those inclination angles which deviate extensively from

Figure 9A. Satellite Model (Front View) Showing Graticule

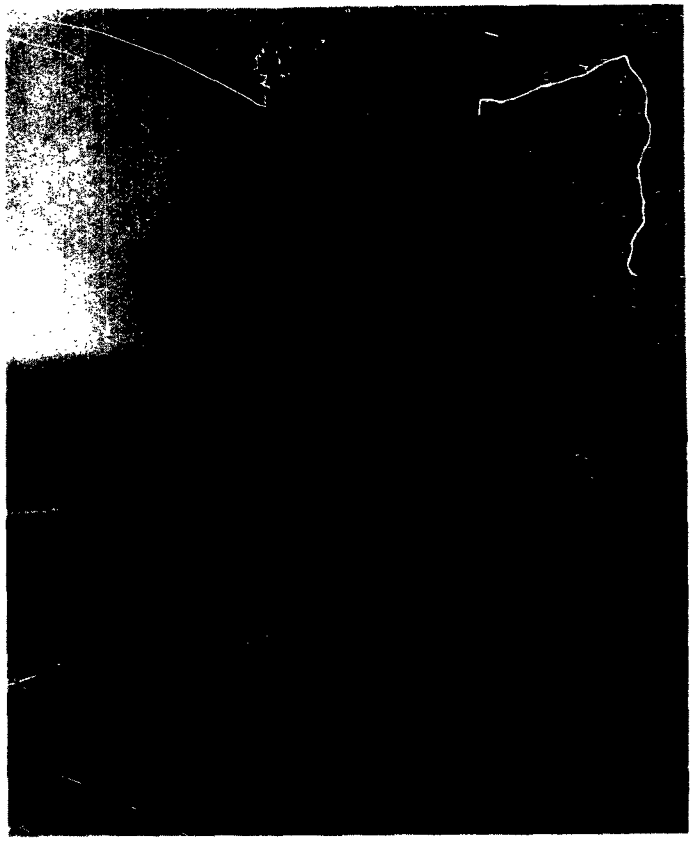


Figure 9B. Satellite Model (Rear View) Showing Pitch and Yaw Angle Scales

90 degrees, no curvature exists in the actual trajectory contained in the orbital plan. Therefore the trajectory cards of the SATRAK are set properly on a straight card for any inclination angle.

If a computer-determined ephemeris is used, the only important error introduced in setting up the SATRAK is the intermediate trajectory card position as described above in 3.3.3.

3.3.5 Averaging and Smoothing Technique for Reducing Error

For those problems in which the SATRAK is set up symmetrically with the base, readings made on each side of the observation point will be mirrored. The resulting redundancy can be used to gain improved accuracy through averaging, or if desired, the number of readings can be cut in half.

When the aspect data is plotted, smooth curves should result. Best fit techniques can be applied which reduce the errors occurring in individual readings.

3.3.6 Refraction Effects

Because the SATRAK implies free-space propagation, the effects of atmospheric refraction for elevation angles above 3 to 5 degrees can be ignored. For elevations near the horizon, however, the effective earth radius is increased and atmospheric refraction must be considered. In practice, such perturbations can be taken into account at the radar or in an associated computer program. The bending of the radar beam is a complex function of radar frequency, water vapor, temperature gradients, and earth topography. It is sufficient for the intended uses of SATRAK to know that refraction results in an effective increase of earth radius, usually approximated as 4/3 actual radius. Awareness of this phenomenon should alert the user in those instances where such a consideration is important to the problem at hand.

4.0 CONSTRUCTION

The SATRAK consists of three major parts: the base, including the simulator, one or more trajectory cards, and the satellite model. Each of these will be described in detail sufficient to permit model shop construction of a complete SATRAK.

4.1 BASE

The base consists of a piece of 1/4-inch Lucite (46 inches x 30 inches) with engraving, as shown in Figure 10. The Lucite sheet is supported by a 3/4 inch plywood base and three aluminum angle stiffeners. The primary scale is 50 nautical miles per inch such that the engraved semi-circles are located at two-inch intervals labeled 2, 3, 4, and so forth, which refer to hundreds of nautical miles. As may be seen in Table 1, the base semi-circle radii are not exactly four inches, six inches, eight inches, and so forth, because these numbers refer to earth ranges and the base circles are projections of the earth range circles. Figure 10 shows the relationship between the base radii and the earth surface ranges. The supporting base for the radar simulator is located such that the point of observation is included in the reference plane perpendicular to the base and at a height exactly six inches above the base. An azimuth scale is provided which reads ±90 degrees from mid-pass azimuth. Alternatively, the azimuth scale can be made a full 360 degrees which, if positioned with the reference plane pointing North and South, will read true bearing. Reversing the North and South reference would then require rotating the circular azimuth indicator 180 degrees.

The elevation indicator is engraved with zero degrees horizontal to the base with angles minus 10 degrees to plus 90 degrees provided in one degree increments. A spring and spool arrangement is provided inside the simulated radar base structure which pays out string under tension to the aspect indicator when attached to the satellite model. Slant range can be found by measuring along the length of the string from the point of exit in

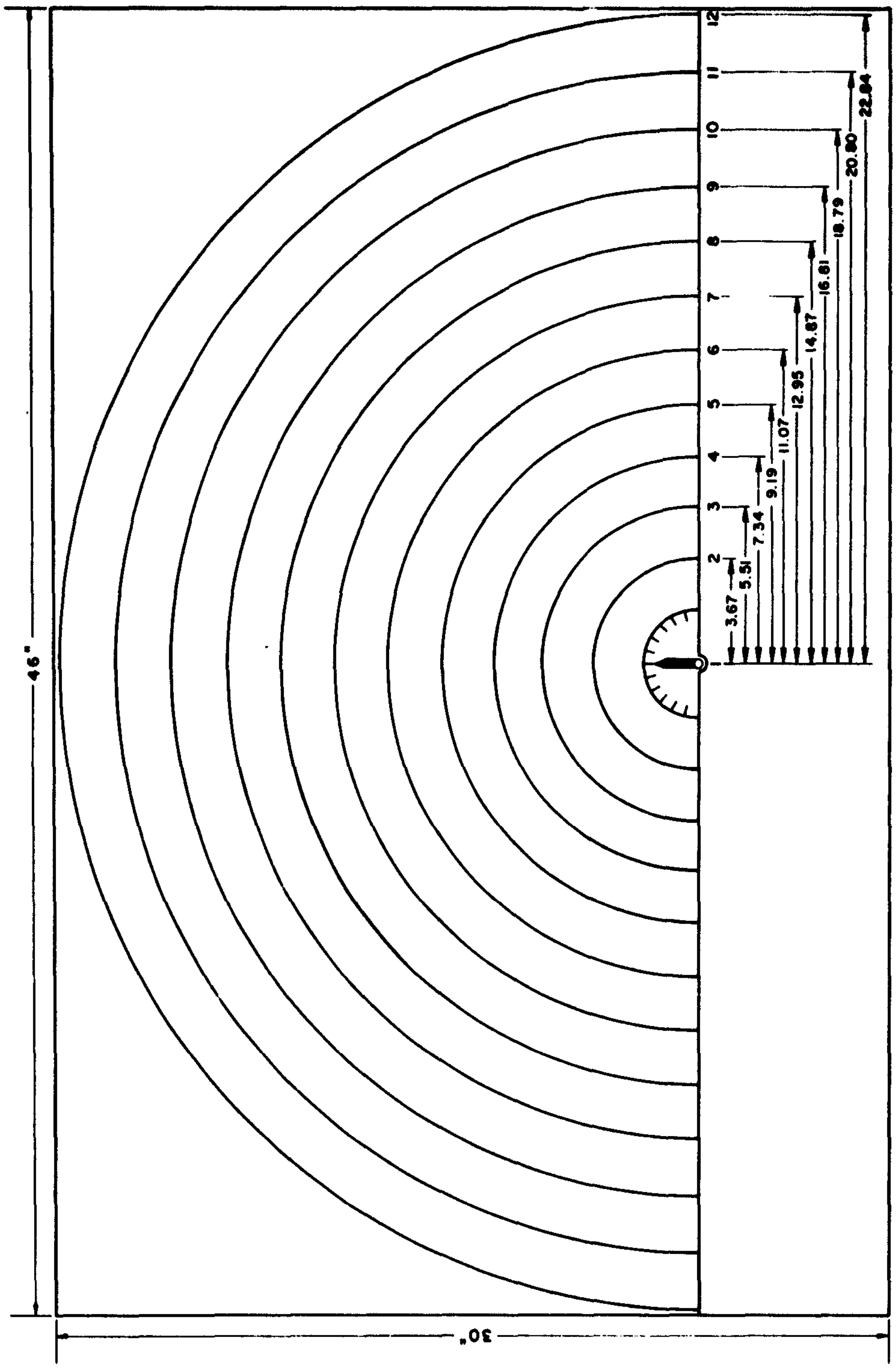


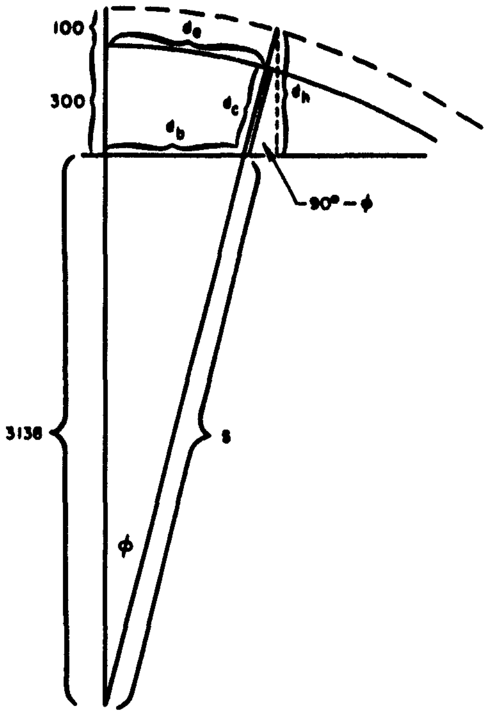
Figure 10. SATRAK Base

Table I. Construction Dimensions

$d_b = 3138 \tan\phi$

$d_c = 3438 - \dfrac{3138}{\cos\phi}$

$d_h = \cos\phi\,(d_c + 100)$



Scale: 50 n mi = 1 inch

CARD	d_b		ϕ	$\cos\phi$	$\frac{3138}{\cos\phi}$	d_c		$d_c + 100$*	d_h	
	n mi	inch				n mi	inch		n mi	inch
1.	90.9	1.8	1.66	.99958	3139	299	5.98	399	399	7.98
2.	182.8	3.67	3.33	.99831	3143	295	5.90	395	394	7.88
3.	275.7	5.51	5.00	.99619	3150	288	5.76	388	387	7.74
4.	366.8	7.34	6.67	.99324	3159	279	5.58	379	376	7.52
5.	459.5	9.19	8.33	.98944	3171	267	5.34	367	363	7.26
6.	553.3	11.07	10.00	.98481	3186	252	5.04	352	347	6.94
7.	647.5	12.95	11.67	.97934	3204	234	4.68	334	327	6.54
8.	743.7	14.87	13.33	.97304	3225	213	4.26	313	305	6.10
9.	840.1	16.81	15.00	.96593	3249	189	3.78	289	279	5.58
10.	939.5	18.79	16.67	.95799	3276	162	3.24	262	251	5.02
11.	1039.8	20.80	18.33	.94924	3306	132	2.64	232	220	4.40
12.	1142.1	22.84	20.00	.93969	3339	99	1.98	199	187	3.74

*Arbitrary value of altitude chosen for illustration.

the tube to the end of the string, then adding a fixed range increment which represents the distance from the end of the string nearest the satellite model to the center of the model.

4.2 TRAJECTORY CARDS

Eleven full trajectory cards are provided indicating each hundred nautical miles beginning with 200 nautical miles surface range. In addition, a partial card is provided for zero range which simulates an overhead pass. (It is intended to add another partial card for the 100 nautical mile range.) Model detail is related to earth geometry in Figure 11. Each card is made of 1/4 inch Lucite with a radius of 68.76 inches, which corresponds to the earth's radius scaled 50 nautical miles to the inch. Center height for each card was calculated as indicated in Table I and is measured along the card surface to the upper edge at its highest point along the surface nearest the simulated radar. This is the reference surface and is used to set up range position as read on the base. The upper edge of each trajectory card is marked off each 1/2 inch representing 25 nautical miles starting at the center position and working in each direction. Angle supports are machined for associated earth angle as indicated in Table I. A base section for each of the three supports is provided approximately 1 inch by 1-1/2 inch so that double coated pressure sensitive tape can be used for holding the cards in position. The edge of each card support, which touches a trajectory card, is cemented permanently. Doubling the basic scale necessitates new cards with halved surface radii and recalculated support angles.

4.3 SATELLITE MODEL

The satellite model is constructed of brass and consists of a base slider 2-1/4 inches long, 5/8 inch thick and 1 inch high. A thumb screw is provided. This positively positions and locks the model while readings are taken. A yaw scale is attached to the upper surface of its base, see Figure 9B. A pedestal is formed by assembling stud sections providing lengths of 0.2 inch, 0.4 inch, 0.8 inch and 1.6 inch. At the upper end of the

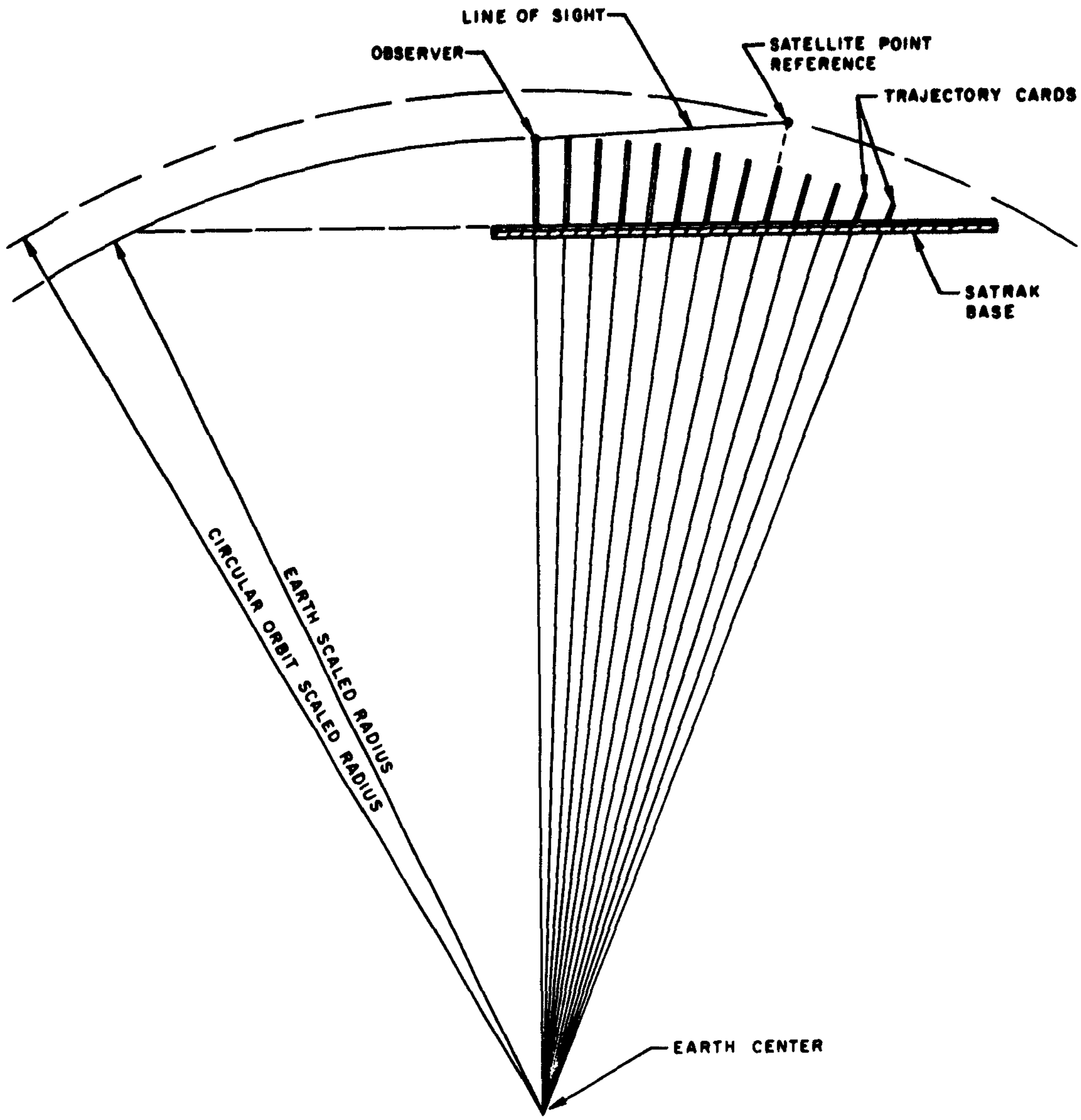


Figure 11. Model Detail Related to Earth Geometry

stud section is located a 1/4 inch x 3/8 inch x 1/8 inch ball bearing. The ball bearing supports the rotating arc which carries the aspect indicator. The arc has an inner radius of 1-5/16 inch and must be accurately machined to avoid error and assure free movement of the indicator. The arc center is the point satellite reference. The indicator contains a small ball bearing 3/16 inch x 1/16 inch x 1/8 inch. An angle support 1 inch x 1-5/8 inch is provided to support the graticule assembly. Centered on its 1 inch base is a hole which fits a supporting shaft and is held to the shaft by a set screw. When loosened, the screw permits yaw adjustment. In the upright part of this angle piece is a hole 1-1/4 inch from the base through which a 6-32 thumb screw passes surrounded by a 3/16 inch sleeve. This arrangement permits rotating and locking the graticule assembly in pitch. The graticule assembly consists of a 1/16 inch circular plate 2 inches in diameter. The graticule is a 2 inch transparent Lucite sphere about 1/10 inch thick with a 3/16 inch extension which is a portion of a 2 inch Lucite cylinder (see Figure 6). The graticule is engraved each 10 degrees in θ and ϕ as indicated in Figure 1. Roll motion per se is not provided, but is seen as a semi-circular wire fiducial which pivots at the nose and tail of the satellite model inside the hemispherical graticule. This can be seen in Figures 6 and 9A. Roll is simulated by removing the graticule and positioning the roll fiducial to the desired angle. The angle which the fiducial represents is either 0 to 180 degrees or 180 to 360 degrees depending upon the direction given the satellite replica inside the graticule.

Details of the satellite model construction may vary, but it is important that yaw, pitch, and roll be introducible into the model in precisely the order given above.

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